design**feature** *By Ronnie D Hughes, National Semiconductor*

ALL OF TODAY'S PC DESIGNS–INCLUDING DESKTOP, NOTEBOOK, AND SERVER PLATFORMS–REQUIRE THERMAL MANAGEMENT.

Remote diodes yield accurate temperature measurements

WITH CPUs AND CHIP SETS running at clock speeds that were once thought of only in terms of UHF and microwave communications frequencies, heat generation is a problem for PC-system designers. The reliability or MTBF (mean time between failures) of silicon-semiconductor devices exponentially relates to the temperature of the die.

To prevent failures, you must incorporate thermal-management features in your design. You can control temperatures by, for example, lowering device voltages and reducing clock rates so that devices generate less heat, or by increasing airflow so that the system can better dissipate heat into its environment. However, each method has its drawbacks. Slowing the clock results in reduced performance, and increasing fan speed or adding fans increases acoustic noise. If you can accurately measure critical temperatures, the system can lower clock frequencies and increase fan speed only when necessary. This approach allows the system to operate at maximum performance levels and as quietly as possible while keeping the chips operational. The more accurately you can measure critical temperatures, the closer to design limits the system can operate before temperature-lowering methods impact performance or make the noise level objectionable.

MEASURING TEMPERATURE

Because die temperature is a critical parameter, some devices incorporate a means to allow you to measure it—normally, a diode or a diode-connected transistor near the hot spot on the die, commonly referred to as a *thermal diode*. You can readily find sensors, typically called *remote-diode-temperature sensors,* that connect to and use thermal diodes to measure chip temperature. The LM86 from National Semiconductor is a typical representative of such a class of devices. The LM86 data sheet lists equivalent devices from other vendors. These sensors provide an accuracy of ±1°C when the remote diode's temperature is 60 to 100°C. At first glance, this information looks straightforward, but a graph in the LM86 data sheet shows errors greater than 12°C and −4°C when you use the device with an Intel Pentium IV at 120°C. Overall accuracy involves more than just the temperature sensor's accuracy.

The forward voltage for a diode or a diode-connected transistor (p-n junction) is:

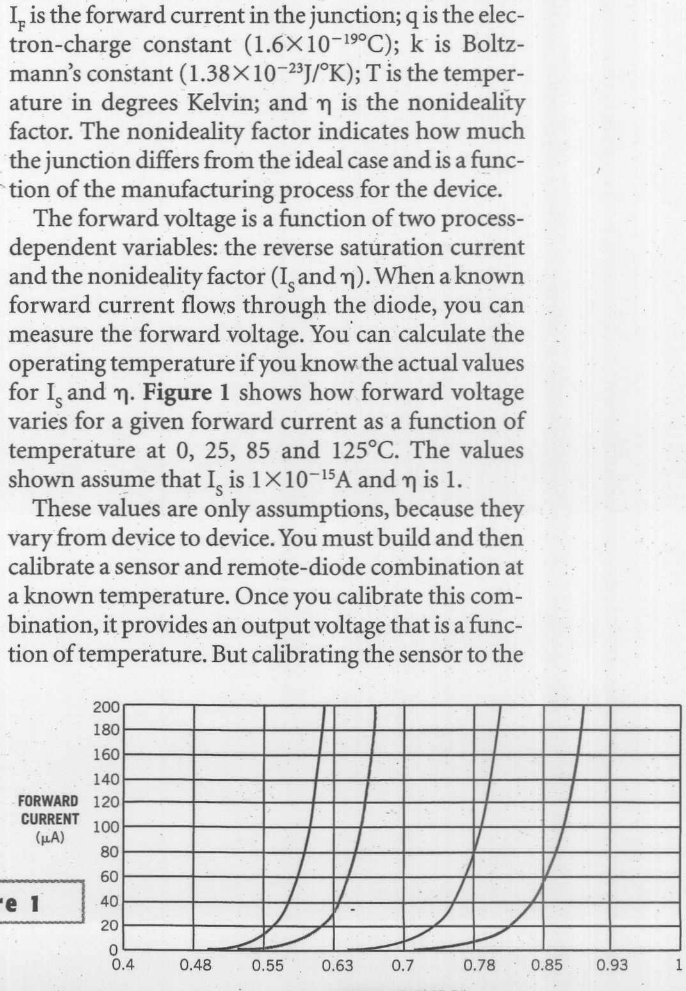
$$V_F = \eta \bullet \frac{kT}{q} \ln\left(\frac{I_F}{I_S} - 1\right), \qquad (1)$$

where I_S is the reverse saturation current (typically around 10^{-15}A for silicon but process-dependent); I_F is the forward current in the junction; q is the electron-charge constant (1.6×10^{-19}°C); k is Boltzmann's constant (1.38×10^{-23}J/°K); T is the temperature in degrees Kelvin; and η is the nonideality factor. The nonideality factor indicates how much the junction differs from the ideal case and is a function of the manufacturing process for the device.

The forward voltage is a function of two process-dependent variables: the reverse saturation current and the nonideality factor (I_S and η). When a known forward current flows through the diode, you can measure the forward voltage. You can calculate the operating temperature if you know the actual values for I_S and η. **Figure 1** shows how forward voltage varies for a given forward current as a function of temperature at 0, 25, 85 and 125°C. The values shown assume that I_S is 1×10^{-15}A and η is 1.

These values are only assumptions, because they vary from device to device. You must build and then calibrate a sensor and remote-diode combination at a known temperature. Once you calibrate this combination, it provides an output voltage that is a function of temperature. But calibrating the sensor to the

Figure 1



Temperature affects the diode forward voltage.

remote junction is impractical in high-volume-production processes.

A different measurement technique simplifies the calibration step. By using two known current sources with a fixed ratio of N, you can eliminate the effect of I_S (**Figure 2**). In this approach, you take one measurement of forward voltage using I_F and a second measurement of forward voltage using $N{\cdot}I_F$. This difference in voltage, or ΔV, is a function of only temperature and η and does not depend on I_S . The following equations illustrate the math steps necessary to arrive at this conclusion.

$$V_F = \eta \bullet \frac{kT}{q} \ln\left(\frac{I_F}{I_S}\right). \quad (2)$$

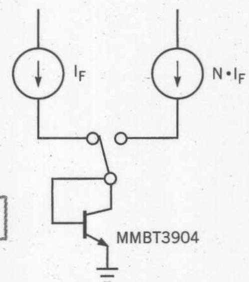
$$\Delta V_F = \eta \bullet \frac{kT}{q}\left\{\ln\left(\frac{N \bullet I_F}{I_S}\right) - \ln\left(\frac{I_F}{I_S}\right)\right\}. \quad (3)$$

$$\Delta V_F = \eta_D \bullet \frac{kT}{q}\ln(N). \quad (4)$$

Equation 2 is a simplification of **Equation 1** with the elimination of the −1 term, because its value is smaller than the other terms. You thus derive a ΔV voltage value that is a function of the diode temperature, the nonideality factor of the diode, and the ratio of the current sources in the temperature sensor.

Remote-diode-temperature sensors take two measurements to arrive at a temperature reading; the first uses a single current source, and the second uses N times that current source. The current ratio in the LM86 device is 16. To get a feel for the change in magnitude of ΔV as a function of temperature, solve **Equation 3** for a couple of temperatures—say 84 and 85°C. You discover that a change of 1°C changes ΔV by only 241 μV. The discussion on noise issues further considers this fact.

Figure 2



A dual-current-source measurement arrangement eliminates the effect of I_S.

You can solve **Equation 3** for temperature, which is in effect what the temperature sensor does. It takes two voltage measurements; subtracts to get ΔV; and converts this value into a temperature reading, T_{OUT}. A temperature sensor calibrated at some value of nonideality factor is necessary to perform this conversion. If the temperature sensor's nonideality factor matches that of the diode, no error results. When the diode's nonideality factor does not match the assumed nonideality factor in the temperature sensor, either because of a different manufacturing process or because of part-to-part variations, an error in the temperature reading results.

Equation 3 gives the voltage that the diode produces based on its nonideality factor. It bases the temperature-sensor calculation on its assumed nonideality factor given in **Equation 4**:

$$T_{OUT} = \frac{\Delta V_F \bullet q}{\eta_S \bullet k \bullet \ln(N)}. \quad (5)$$

By substituting **Equation 4** into **Equation 5** and simplifying, you arrive at:

$$T_{OUT} = \frac{\eta_D}{\eta_S} \bullet T, \quad (6)$$

which expresses the temperature reading that the sensor produces as a function of the ratio of nonideality factors of the diode and the sensor. If these factors are not equal, errors in the temperature reading results.

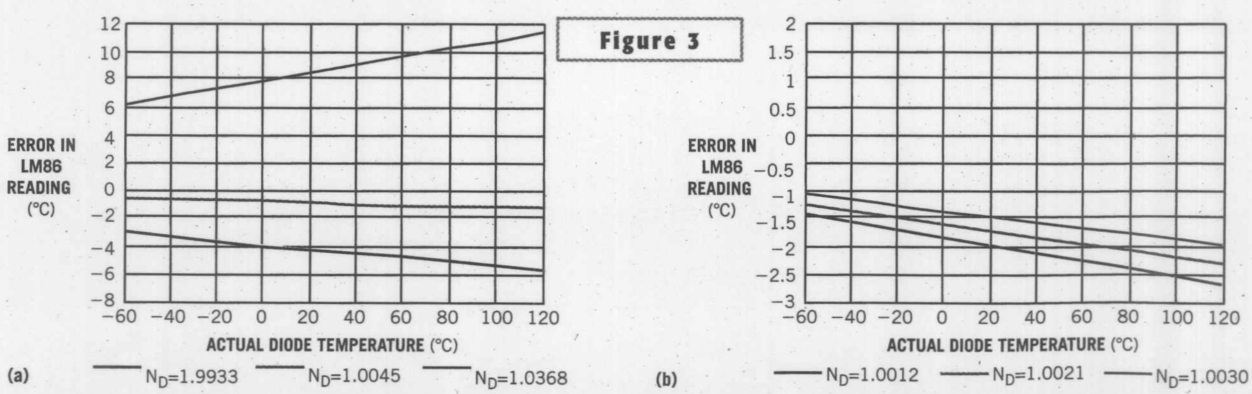
EXAMPLES USING ACTUAL DEVICES

Table 1 provides the specified nonideality factors from several Intel CPU data sheets. Many temperature sensors match a nonideality factor of 1.008, typical of 2N3904- and 2N3906-type transistors. This value is also the typical value of Intel Pentium IIIs. Therefore, this CPU-and-sensor combination provides excellent results with minimum error. However, using such sensors with the Pentium IV, non-0.13-micron processor can result in substantial errors (**Figure 2**).

Matching the thermal-diode nonideality factor and temperature sensor's assumed or calibrated nonideality factor is a key to minimizing error. (**Figure 3b**). In a 1.008-nonideality-factor sensor with an Intel Pentium IV, 0.13-micron processor when the diode's nonideality factor does not match but you hold it to tighter tolerances, the minimum and maximum errors are much closer with a spread of less than 1°C at the highest temperature.

Although the Pentium IV, 0.13-micron processor has a much narrower nonideality factor, engineers need to consider another issue. In later product data sheets, Intel specifies the typical series resistance associated with the thermal diode to allow more accurate temperature measurements. The typical series resistance is 3.64Ω for the Pentium IV 0.13-micron desktop processors and 3.86Ω for the mobile version. The series resistance is the internal resistance of the diode circuit, including pin resistance. It includes no socket or external trace re-

Figure 3



Using the LM86 with a Pentium IV, 0.13-micron CPU results in errors (a). But holding the diode's nonideality factor to tighter tolerances results in much closer minimum and maximum errors (b).

sistance, for which Intel publishes only a typical value.

Series resistance adds an offset to the differential voltage that the temperature sensor measures (**Figure 4**). With no series resistance, ΔV is only a function of the diode characteristics and the measurement-current sources. When series resistance is present, ΔV increases, and **Equation 7** gives the impact to the temperature reading:

$$T_{OUT} = \frac{(N-1) \bullet I_{MIN} \bullet R \bullet q}{\eta_S \bullet k \bullet \ln(N)}. \qquad (7)$$

where I_{MIN} is the minimum current source, N is the ratio of the current sources, R is the total series resistance, and η_S is the calibrated nonideality factor of the temperature sensor.

The error that the series resistance produces is a positive offset that you add to the temperature reading, but the magnitude varies with the temperature sensor's measurement-current-source tolerances.

Three examples illustrate the range of errors that can result from series resistance. You can use 1Ω to represent maximum trace resistance and the actual series resistance from two Intel CPU data sheets. The LM86 temperature sensor uses a current-source ratio of 16. Its unity-current-source specification ranges from 7 to 20 μA. A sensor with a lower current ratio produces lower offset errors, but you must balance these errors with the level of ΔV and noise susceptibility. **Table 2** shows the temperature offsets from the series resistances.

Series resistance adds a positive offset to the temperature reading. The following equation combines the nonideality and series-resistance terms and allows the computation of the resulting temperature reading:

$$T_{OUT} = \frac{\eta_D}{\eta_S} \bullet \left(T + \frac{(N-1) \bullet I_{MIN} \bullet R \bullet q}{\eta_S \bullet k \bullet \ln(N)} \right). \qquad (8)$$

Solving **Equation 8**, you find that the overall error falls within −0.82 to +3.3°C when you use an LM86 with a Pentium IV, 0.13-micron mobile processor over the operating range of 40 to 100°C. Typically, engineers characterize a few systems to establish the average error in the temperature reading and subtract the average offset from the reading. Some of the sensors feature an internal offset register for this purpose.

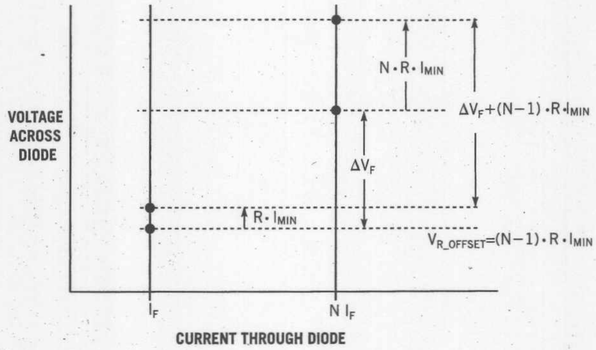


Figure 4 **The series resistance across the thermal diode impacts ΔV.**

The nonideality factor and the series resistance are the major factors in achieving accuracy in temperature readings, but noise and thermocouple effects can also create problems. A small amount of electrical noise can produce a 1°C error in the temperature reading. **Equations 2** through **4** show that a change of 1°C impacts ΔV by approximately 241 μV. Therefore, a noise-induced voltage change of 241 μV during a measurement cycle will result in a 1°C error in the reading. The diode inputs of the temperature sensor (D+ and D−) are differential, helping considerably to lower noise susceptibility over single-ended inputs. Some sensors also contain a digital filter to help combat noise. Using software controls, you can enable and configure typical running average filters to one of two filter levels. However, proper board layout is important. Some recommendations to reduce the chance of noise-induced problems are to route the D+ and D− leads as close together as possible and to keep the D+ and D− leads as symmetrical as possible. You should also route the ground traces on both sides of the D+ and D− pair and place the temperature sensor as close as possible to the thermal diode. Route D+ and D− as far as possible from other traces and arrange for D+ and D− traces to cross other traces at 90° angles when possible.

When two dissimilar metals are in contact, the thermocouple effect produces a small voltage that is proportional to temperature. A typical solder-to-copper junction exhibits a 3-μV/°C output. Although this effect rarely causes significant problems in pc boards, you can minimize it by limiting the number of copper-to-solder joints in the traces to the thermal diode and ensuring that the D+ and D− traces have the same number of dissimilar metal junctions. You could also place D+ and D− dissimilar metal junctions where their temperatures are equal.

To minimize external series resistance errors, place the temperature sensor as close as possible to the thermal diode, avoid the use of socket connections in the thermal-diode circuit path, use trace widths that measure at least 10 mils wide, and ensure good solder connections in the thermal-diode circuit.

Accurate temperature measurement is the basis for intelligent thermal management in PCs. Good thermal-management design allows for greater system performance and quieter audible noise levels.□

TABLE 1—NONIDEALITY FACTORS

Intel processor type	Nonideality factor Minimum	Typical	Maximum
Pentium 3	1.0057	1.0080	1.0125
Pentium 3, 0.13 micron	1.001452	1.007152	1.012852
Pentium 40.9933	1.0045	1.0368	
Pentium 4, 0.13 micron	1.0011	1.0021	1.0030

Courtesy Pentium 3 and 4 data sheets

TABLE 2—TEMPERATURE-READING ERRORS (POSITIVE OFFSETS) RESULTING FROM SERIES RESISTANCE

Series resistance (Ω)	Temperature when I_{MIN} = 7 μA (°C)	Temperature when I_{MIN} = 20 μA (°C)
1	0.436	1.245
3.64	1.586	4.530
3.86	1.681	4.804

AUTHOR'S BIOGRAPHY

Ronnie D Hughes, a field applications engineer with National Semiconductor (Austin, TX), has more than 20 years' experience as an engineer. In his current position, he works on PC-targeted products, including super I/O, networking, power regulation, system-health monitoring, and wireless communications. He received his master's and bachelor's degrees in electrical engineering from Mississippi State University.

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